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Spatial Variability of Groundwater Recharge - I. Is it really variable?

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Abstract
The spatial variability of recharge is an important consideration in estimating recharge especially as all methods of estimating it are 'point' estimates and in most places recharge varies in space. This paper along with the accompanying paper attempts to find a suitable answer to the question of taking this variability into account in estimating groundwater recharge. This paper attempts to determine if recharge is actually varying in space and that this is 'true' variability and that it is not an artefact of the method used for estimating recharge. It also pulls together information on spatial variability of recharge reported by various workers in the literature, in order to determine if recharge is truly variable in space.

Keywords
Spatial variability, Groundwater recharge, Sri Lanka

1. INTRODUCTION

The rate of replenishment of the water table in aquifers (mainly by rainfall) is known as the groundwater recharge rate. This is the most important parameter required in the successful development of groundwater resource, as often it is this rate (or amount per unit time) that can safely be abstracted as safe yield from wells and bore-holes from a particular aquifer.

There are a number of methods of estimating the groundwater recharge rate to an aquifer. They are (a) lysimeter method, (b) soil water budget models, (c) water table fluctuation method, (d) catchment water balance method, (e) numerical modelling of the unsaturated zone (f) zero flux plane method and (g) Darcy method (h) tritium profiling method and (i) chloride profiling method (Lerner et al, 1990; de Silva, 1996; de Silva, 1998; Scanlon et al, 2002). Except for the catchment water balance (which is a hardly used method nowadays with a number of short comings such as difficulties in identifying catchment boundaries, taking account of cross flows, non availability of catchment wide data and non availability of data such as irrigations and abstractions), all the other methods yield a point estimate. However, groundwater recharge is likely to vary in space even over short distances as variations in soil and vegetation parameters can significantly affect the rates of recharge (Cook et al, 1989). Therefore, taking account of spatial variability in estimating recharge is very important if reasonably accurate replenishment rates to the water table are to be estimated.

This paper attempts to answer the following important questions about the spatial variability of groundwater recharge. [The term spatial variability in this paper in general refers to variability in plan over small areas (about 100 m x 100 m)].

(a) Is groundwater recharge variable in space over small areas?

(b) If recharge is spatially variable, could this apparent variability be due to experimental error and/or due to uncertainties involved in the process of recharge estimation rather than true variability?

2. MATERIALS AND METHODS.

The methodology used is to estimate recharge using the chloride profiling method at a few locations and then to analyse the experimentally obtained data and also data reported in the literature to provide answers to the questions raised in section 1.

2.1 Study locations.

The study locations chosen are as shown in Fig. 1. Table 1 summarises the climatic, soil and vegetation information at each study location. Full details of these locations and reasons for selecting these stations as study locations are given in de Silva (1996).

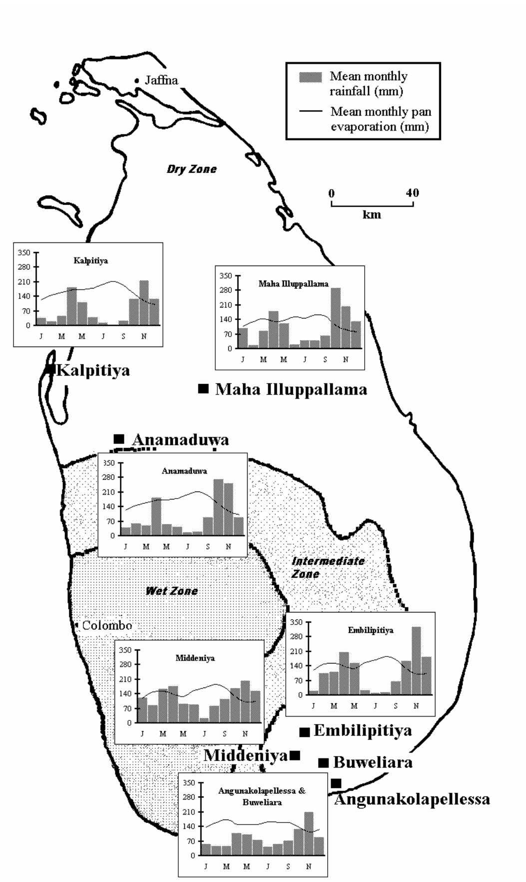


Fig. 1 Study locations (and their climates) in the dry zone of Sri Lanka (Wet, Intermediate and Dry zones of Sri Lanka are also shown).

Table 1 Climate, soil and vegetative parameters at study locations.

Location Name and acronym used	No of holes augured	Mean Annual Rain[1] (mm/y)	Mean Annual Pan Evaporation[1] (mm/y)	Vegetation	Major Plant type	Top soil
Embilipitiya (**EMB**)	8	1397	1729[2]	Shrub jungle	Maana (Grass about 30 cm tall)	Loamy Sand
Middeniya (**MID**)	16	1484	1729[2]	Mango and Teak Plantation	Eluk (Grass about 30 cm tall)	Sandy Loam
Buweliara[3] (**BWA**)	12	1041	1868	Shrub jungle	-	Sandy clay Loam
Angunakola-pellessa (**AKP**)	12	1041	1868	Shrub jungle	Eraminiya (Bush about 1.5 m tall)	Sandy Clay Loam
Maha Illuppallama (**MI**)	8	1305	1579	Jungle	-	Loamy Sand
Anamaduwa (**AMD**)	1	1117	1958[4]	Jungle	-	Sandy loam
Kalpitiya (**KAL**)	5	955	1958[4]	Sparse Jungle	Bolpana (Tree about 3m tall)	Sand

[1] 6 year mean value except for Angunakolapellessa and Buweliara where the mean values are 17 year ones
[2] Pan evaporation values are from the nearest climate station at Sevanagala.
[3] Since no rainfall or pan evaporation data are available for Buweliara, data from the nearest climatic station (Angunakolapellessa) is used.
[4] Pan evaporation value are from nearest climate station at Vanathavillu.

2.2 Estimation of groundwater recharge

Recharge was estimated using the unsaturated zone chloride profiling method at all sampling points at each study location. Environmental chloride is deposited on land by atmospheric deposition processes (rainfall + dry fallout). If the chloride present in the unsaturated zone has atmospheric deposition as its source and there exists no other source or sink in the unsaturated zone for the chloride ions, then under steady state conditions assuming piston flow, it is possible to obtain a chloride mass balance for the chloride flux entering and leaving the root zone as given below.

$$R_e = \frac{C_p}{C_z} . P \quad \text{.....................(1)}$$

where Re = recharge rate leaving the root zone (mm/yr)

C_Z = mean chloride ion concentration in soil water (mg/l)

P = precipitation (mm/yr)

C_p = chloride ion concentration in rainfall (mg/l)

Details of the method are found in Allison and Hughes (1978), Edmunds and Walton (1980), Kitching et al (1980), Sharma and Hughes (1985), Edmunds et al (1988), Sukhija et al (1988), Cook et al (1989), Scanlon (1991), Edmunds and Gaye (1994), Kennet-Smith et al (1994), de Silva (1996), Sukhija et al (1996), and de Silva (1998).

2.3 Errors and uncertainties of the method of estimation of recharge

The percentage error in using the chloride profiling method is obtained by taking the differentials of equation 1, as shown in equation 2.

$$\frac{\partial R_e}{R_e} = \frac{\partial P}{P} + \frac{\partial C_p}{C_p} - \frac{\partial C_z}{C_z} \quad \text{……………(2)}$$

Therefore, the errors associated with the chloride profiling method are from

(a). Errors in measuring rainfall (first term on the right hand side in equation 2)

(b). Errors in determining the chloride ion concentration in rainfall (second term on the right hand side in equation 2)

(c). Errors in determining the chloride ion concentration in soil water (third term on the right hand side in equation 2).

2.3.1 Errors in measuring rainfall.

No published work on the error in measuring rainfall in Sri Lankan conditions were found. Therefore as suggested by the Meteorology department (Kumarasinghe, 1995) this was considered as ±1%.

2.3.2 Errors in measuring the chloride ion concentration in rainwater samples

The experimental error results from the errors in the analytical method used to determine the chloride concentration in water samples. In order to determine this, 10 standard solutions of chloride concentration of 20 mg/l were tested in the spectrophotometer and values from 19.37 mg/l to 20.04 mg/l with a mean of 19.72 mg/l and a standard deviation of 0.195 mg/l were obtained. Therefore, the standard error of the mean is ± 0.195/√10 or ± 0.062 and the percentage error is ± (0.062/20) x 100 = ± 0.31%.

2.3.3 Errors in measuring the chloride ion concentration in soil water samples

The experimental error in determining chloride concentration in soil water results from the errors in the extraction process (which consist of weighing soil samples and measuring water volumes) and in determining chloride ion concentration of extracted soil water samples colourimetrically. A soil sample weighed 10 times resulted in readings of between 66.08 g to 66.15 g with a mean of 66.13 g and a standard deviation of .006 g. Therefore, the percentage random error is ± 0.01% in weighing soil samples. Similar results were obtained for measuring volumes (as measurements of volumes were carried out with a micro-pipette wherever possible). Hence the experimental error in determining chloride concentration in soil is primarily due to the analytical method used to determine the chloride concentration in soil water extracts and is equal to ± 0.31% (as obtained in 2.3.2).

Hence the total error (from equation 2) in estimating recharge with the chloride mass balance is ±1% ± 0.31% = ± 1.31%.

2.4 Determination of soil and vegetation parameters

Four sets of concentric ring infiltrometers (diameters of small and large rings were 270 mm and 500 mm, 1.5 mm thick stainless steel sheets respectively and all rings were 300mm tall) were fabricated. Infiltration tests were carried out as described in Rowell (1994) near all the holes augured (except at Kalpitiya), by driving the rings 5 cm into the soil.

Soil samples in the top 1m of each profile were thoroughly mixed and the particle size distribution was determined to obtain the clay content (< 2μm soil particles) using the pipette method (British Standards Institution, 1990b). Table 2 summarises the infiltration rates and clay contents thus found and full details are given in de Silva (1996).

Table 2 Summary of information on spatial variability of recharge in Sri Lanka and other parts of the world.

Case no:	Country	Location	No of estimates at the location	Min estimate of recharge (mm/y)	Max estimate of recharge (mm/y)	Mean estimate of recharge for the location (mm/y)	St Dev of recharge estimates for the location (mm/y)	CV	Mean annual Rain[1] (mm/y)	Mean annual ETp[1] (mm/y)	Soil	Mean Clay content of top soil	Vegetation	Approx. site Area (ha)	Source
1	Sri Lanka	EMB	6	47.9	97.0	66.0	20.0	0.30	1397	1470	Loamy	0.12	Shrubs	4	The present study
2	Sri Lanka	MID	16	4.1	42.2	14.5	9.2	0.64	1484	1470	Loamy	0.16	Grass	4	The present study
3	Sri Lanka	BWA	12	2.9	46.5	18.0	14.0	0.78	1041	1588	Clay loam	0.2	Shrub jungle	2.5	The present study
4	Sri Lanka	AKP	12	3.3	14.9	9.0	3.7	0.40	1041	1588	Clay loam	0.22	Shrub jungle	1.5	The present study
5	Sri Lanka	MI	8	22.8	65.9	42.2	15.0	0.36	1305	1342	Loamy	0.14	Jungle	0.4	The present study
6	Sri Lanka	KAL	5	5.8	44.1	19.0	15.6	0.82	955	1664	Sandy	0.04	Sparse jungle	0.2	The present study
7	UK	Silsoe	33	80.0	233.0	135.5	39.5	0.29	559	616	Sandy Loam	0.08	Grass	-	The present study
8	Senegal	North West	6	4.6	34.4	16.6	12.1	0.73	300	-	Sandy	-	Sparse Shrubs	50	Edmunds and Gaye (1994)
9	Senegal	North West	4	0.5	8.5	2.7	3.9	1.47	300	-	Sandy	-	Sparse Shrubs	-	Edmunds and Gaye (1994)
10	Australia	SA	346	0.0	85.0	19.4	13.4	0.69	340	1800	Sands and Sandy loams	-	Woodland	378	Cook et al., (1989)
11	Australia	WA	5	28.0	60.0	47.0	13.8	0.29	800	1800	Sandy	-	Woodland	0.8	Sharma and Hughes (1985)
12	Australia	NSW	6	6.0	9.0	7.5	1.4	0.18	310	2100	-	0.2	Cropping	-	Kennet-Smith et al., (1994)
13	Australia	NSW	6	3.0	6.0	4.0	1.3	0.32	310	2100	-	0.12	Cropping	-	Kennet-Smith et al., (1994)
14	Australia	NSW	6	5.0	13.0	8.2	3.5	0.43	312	2000	-	0.14	Cropping	-	Kennet-Smith et al., (1994)
15	Australia	SA	6	2.0	8.0	4.7	2.5	0.54	340	1900	-	0.19	Cropping	-	Kennet-Smith et al., (1994)
16	Australia	SA	6	4.0	40.0	18.7	13.8	0.74	340	1900	-	0.1	Cropping	-	Kennet-Smith et al., (1994)
17	Australia	SA	6	1.0	31.0	14.0	11.9	0.85	340	1900	-	0.12	Cropping	-	Kennet-Smith et al., (1994)
18	Australia	SA	5	13.0	39.0	25.2	13.0	0.51	370	1900	-	0.14	Cropping	-	Allison et al., (1990)

Notes : (a) In case no: 7, data for 12 out of the 33 chloride profiles are from Smith (1995). (b). A hyphen indicates that the relevant information is not available.

[1] Rainfall and potential evapotranspiration figures for locations in Sri Lanka are 6 year mean values except for Angunakolapellessa (17 year mean). For Silsoe, UK a 26 year mean is shown. The duration of data in other cases (from no: 8 - 18) are as given in the publications cited.

2.5 Collection of information in other documented studies of spatial variability of recharge.

A literature search was carried out for published works on spatial variability of groundwater recharge and the results of documented studies are summarised in Table 3.

Table 3 Spatial variability of groundwater recharge

Author	Country and Location	Mean Annual Rain (mm/y)	Mean Annual ETp (mm/y)	Soils and Vegetation	Recharge values[1] (mm/y)
Sharma and Hughes (1985)	South-western Coast of Australia	800	1800	Sand (85-90% coarse) with clay bands below 10 m	53, 37, 28, 57, 60 in a circle of 50 m radius (0.008 km^2)
Edmunds and Gaye (1994)	Northwest Senegal	300		Sands with red brown top soil and Sparse vegetation (Acacia)	5 to 35 in an area of 0.5 km^2 (6 point estimates) 1 to 9 (4 point estimates)
Cook et al., (1989)	Southern Australia	340	1800	Sands and Sandy loams	0 to 85 in an area of 3.78 km^2 (346 point estimates)
Johnston (1987b)	Collie in Western Australia	1220	1630	Lateritic clayey soils (30 m deep)	2 to 100 in an area of 700 m^2 (32 point estimates)
Scanlon (1991)	Texas, USA	280	1960	Clay to muddy gravel vegetation shrubs	all values < 1, but vary from 0.01 to .27 in a circle of 2 km radius (10 point estimates)
Allison (1988)	Western Australia	300		Sands and Sandy loams	See below[2]

[1] The method of estimation in all these recharge values have been the chloride profiling method.
[2] chloride values varied from 1500 to 15000 g/m^3 which are believed to reflect recharge values in an area of a circle of radius 100 m).

3. RESULTS

The results obtained are shown in Table 2 (a summary of experimentally obtained results and also of published works), Table 3 (information collected from other published works) and in Fig 2 (three chloride profiles at study location Middeniya). Full details of these results are found in de Silva (1996).

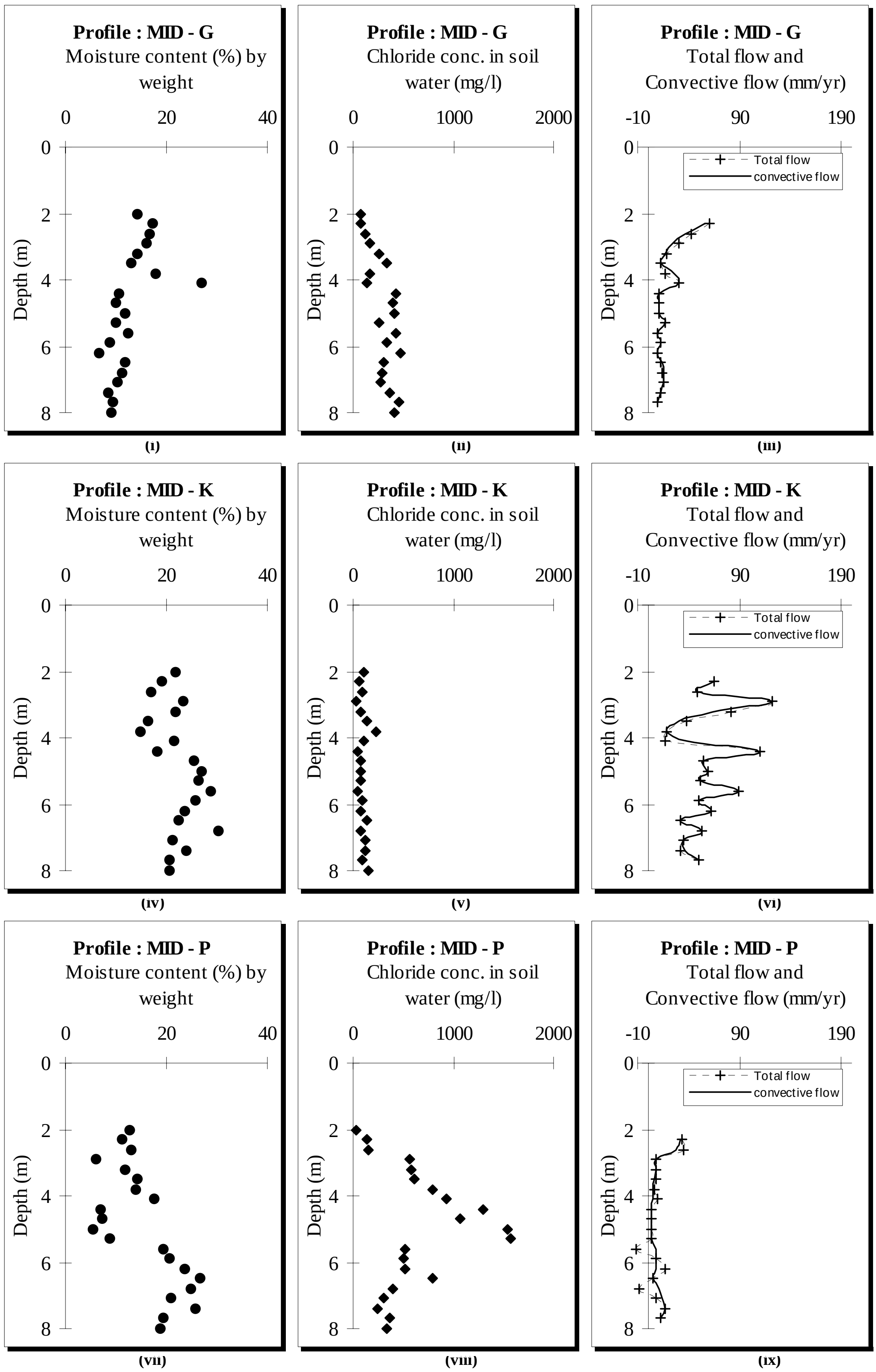


Fig. 2 Moisture content, Chloride conc. and Soil water flux with depth for 3 profiles at Middeniya

4. ANALYSIS OF RESULTS AND DISCUSSION

4.1 Is recharge spatially variable?

Table 3 shows estimates of recharge by various workers in various parts of the world. As can be seen from Table 3, over small areas recharge is quite variable. Table 2 shows the mean, standard deviation, coefficient of variation (CV) and range of recharge values obtained for each study location and also the values of same parameters calculated from recharge estimates reported by different workers. From Table 2, it is seen that the range of recharge estimates is quite high for most locations and also the coefficient of variation (CV) is higher than 0.4 for 12 out of the 18 locations. In Sri Lanka, 4 out of 6 locations have CVs higher than 0.4. At Middeniya (case number 2 in Table 3) in Sri Lanka, recharge estimates vary as much as 10 fold and at South Australia (case no: 17 in Table 2) as much as 31 fold.

Therefore, it is evident that in the dry zone the estimates of recharge over small areas (1 ha) show spatial variability when estimated by the chloride profiling method, as reported for the other parts of the world.

4.2 Could the experimental error and uncertainties of chloride method be the reason for the apparent spatial variability of recharge?

Before confirming that recharge is spatially variable (and that it is not an artefact of the method used to estimate recharge), it is necessary to investigate if any uncertainties in the method of estimating recharge along with the possible experimental errors could be the reason for this apparent variability. Therefore, the following factors need consideration.

4.2.1 Experimental error

The random experimental error in determining chloride concentration in soil was found to be ± 1.31% (de Silva, 1996). Since this error is very small, the contribution of experimental error of the chloride method to the spatial variability of recharge is negligible.

4.2.2 Confidence limits for average chloride concentration (C_z) of a profile.

A typical set of values for chloride concentration with depth for a profile is shown in Fig. 3 below.

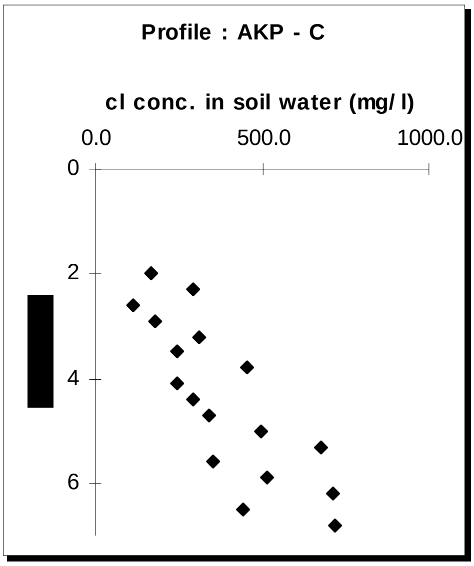
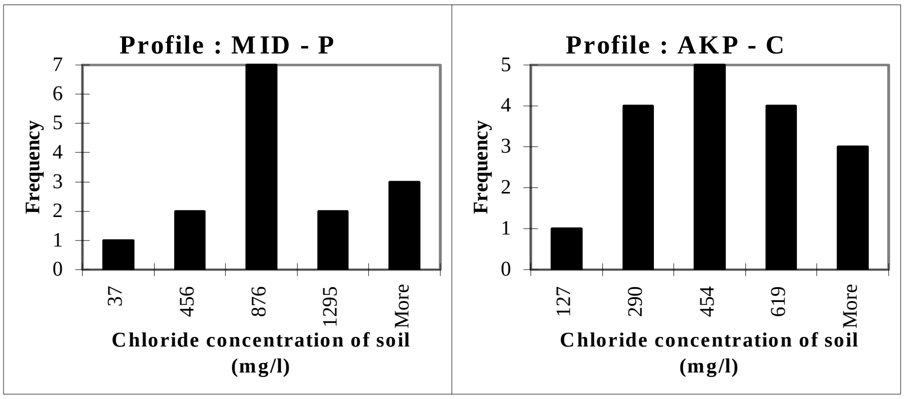


Fig. 3 A typical profile showing chloride concentration in soil water with depth in the dry zone of Sri Lanka

To obtain recharge from equation 1, most workers have averaged the values of chloride concentration below a certain depth (root depth) and used that value as C_z in equation 1. However, this approach does not appear to be correct as this average value (C_z) can vary with the depth augured (e.g., in Fig. 3, the average chloride concentration below the root zone is 216 mg/l if soil samples only up to 4 m are considered whereas the average chloride concentration becomes 377 mg/l if soil samples up to a depth of 5.6 m is considered thus showing a 75% difference). Therefore to increase the chances of obtaining the 'true' value of C_z, confidence limits for the average chloride concentration in soil with depth need to be considered. However, since the number of chloride concentration values in a profile available are small (<30) in the dry zone (because of the depths augured) the frequency distribution of chloride concentration with depth in a profile is required to obtain confidence limits for C_z.

Fig. 4 shows the frequency distribution results of chloride concentrations with depth (below 2m) for 2 profiles. Fig. 3 suggest that the chloride concentrations in soil with depth to be approximately normally distributed.

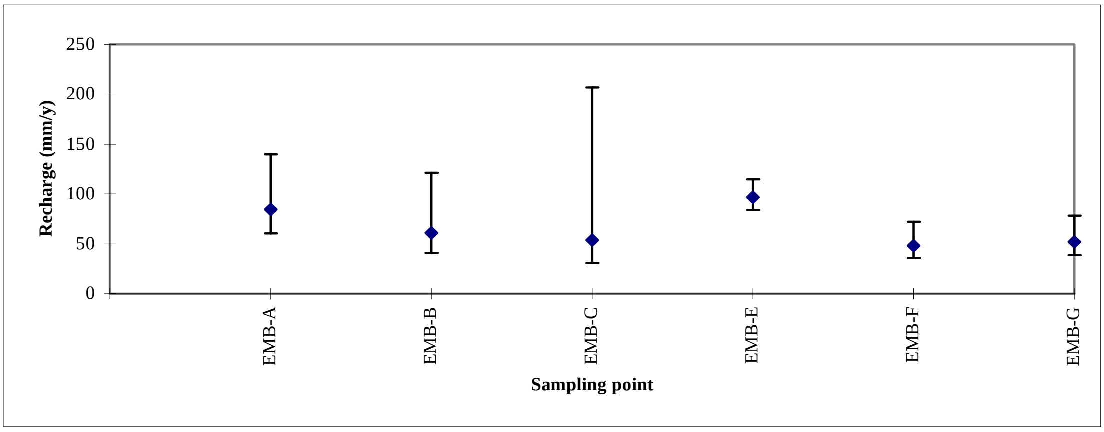


(a) (b)

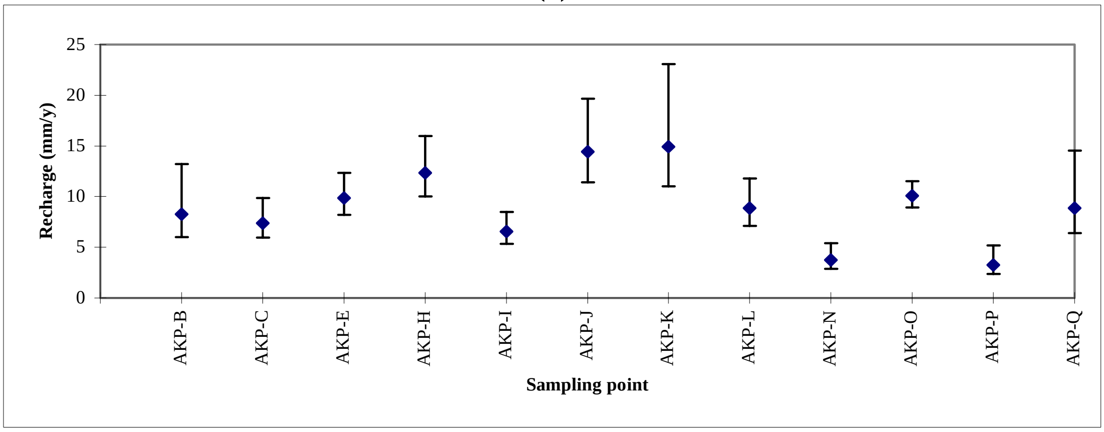
Fig. 4 Frequency distribution of chloride concentrations with depth in profiles for (a) MID - P and (b) AKP - C.

The Shapiro-Wilk test (Rees, 1995) which is useful in determining if a sample follows a normal distribution (when the sample size is small) also confirmed that chloride concentrations in soil in a depth profile appear to follow approximately a normal distribution (de Silva, 1996).

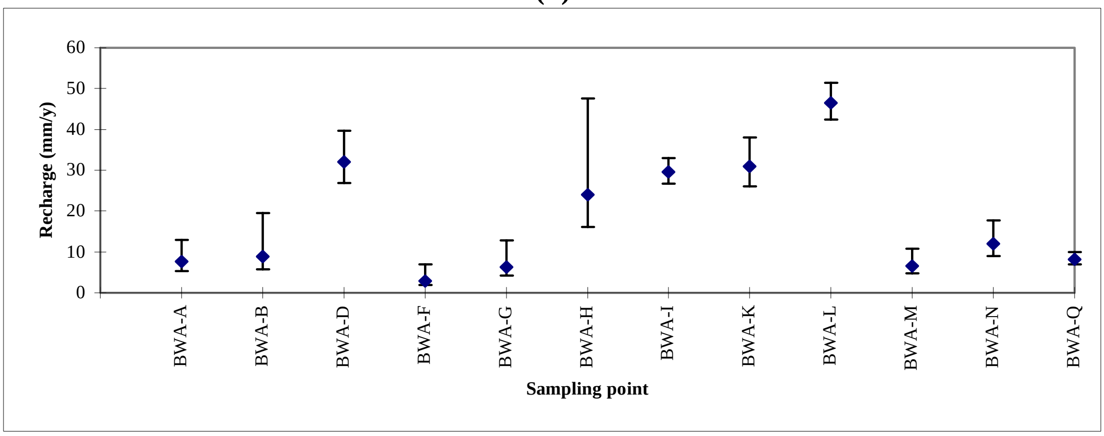
Fig 5 (a), (b), (c), (d), (e) and (f) show the range of recharge values obtained by using 95% confidence limits for chloride concentrations in soil at each profile (from equation 1) for each sampling point at all study locations. An analysis of variance test (Gomez and Gomez, 1976) confirms that the means of ranges are significantly different at 5% significance level, suggesting that there is true spatial variability at each study location.



(a)

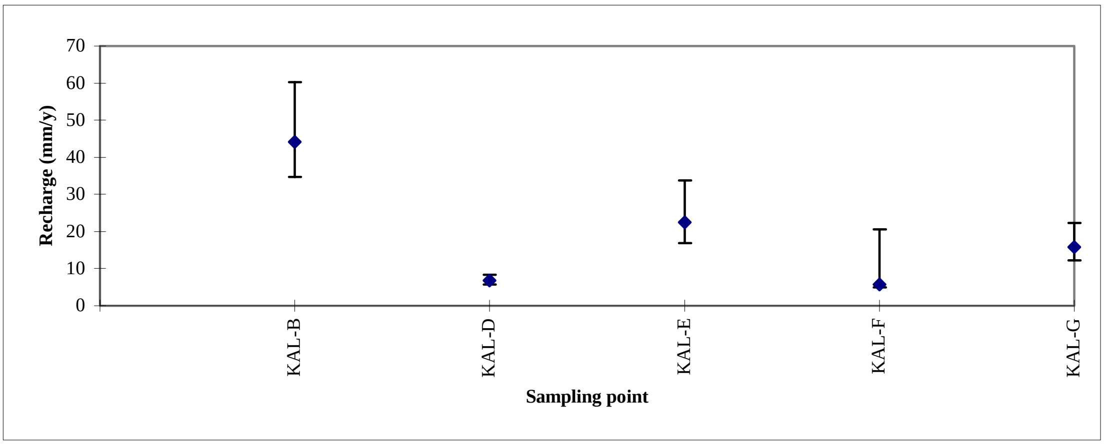


(b)

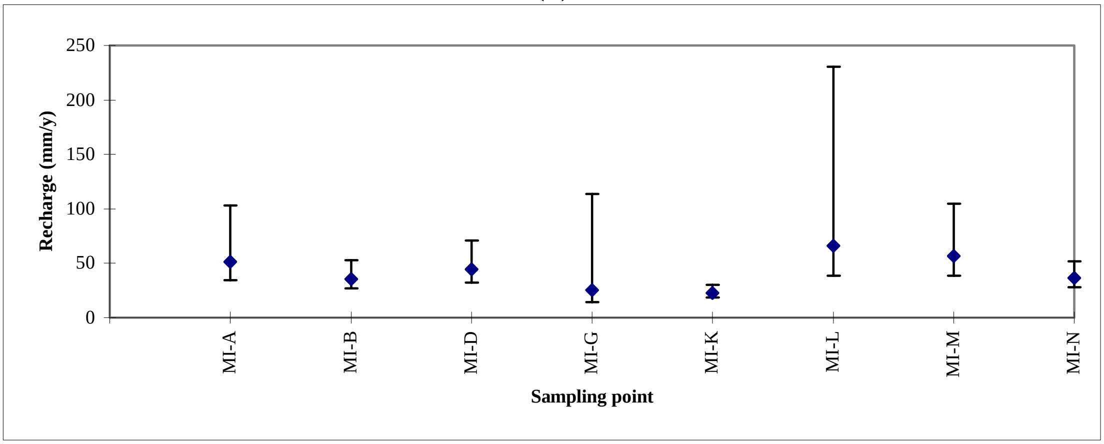


(c)

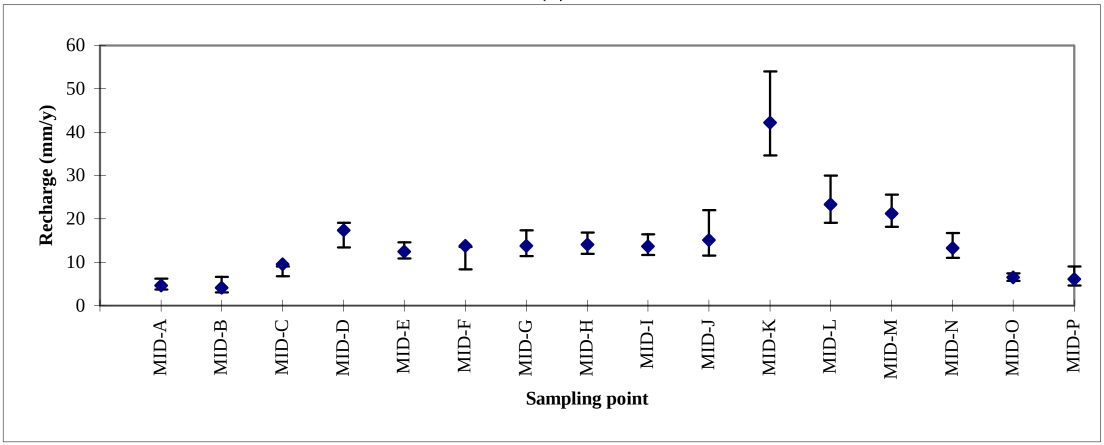
Fig. 5 (a), (b) and (c) Range of recharge possible by considering confidence limits for Cz at locations Embilipitiya, Angunakolapellessa and Buweliara.



(d)



(e)



(f)

Fig. 5 (d), (e) and (f) Range of recharge possible by considering confidence limits for Cz at locations Kalpitiya, Maha Illuppallama and Middeniya.

4.2.3 Different time periods of recharge registered in different profiles

Usually, different profiles transport water at different velocities and therefore the chloride concentrations in soil even at the same depth at two different sampling points could correspond to different recharge regimes resulting from different number of years of recharge history being recorded in the profiles. As Edmunds and Gaye (1994) point out this also could be a reason for the apparent spatial variability.

Fig. 6 shows the likely recharge chronologies recorded at different profiles for the location Angunakolapellessa assuming (a) soil water velocities can be estimated by dividing the soil water flux by the volumetric moisture content, (b) dry bulk density of soil with depth is constant and is equal to 1.3 g/cm^3 and (c) the soil water velocity for the top 2m at each profile is same as that below 2m (this is because no chloride data for the top 2m of soil are available).

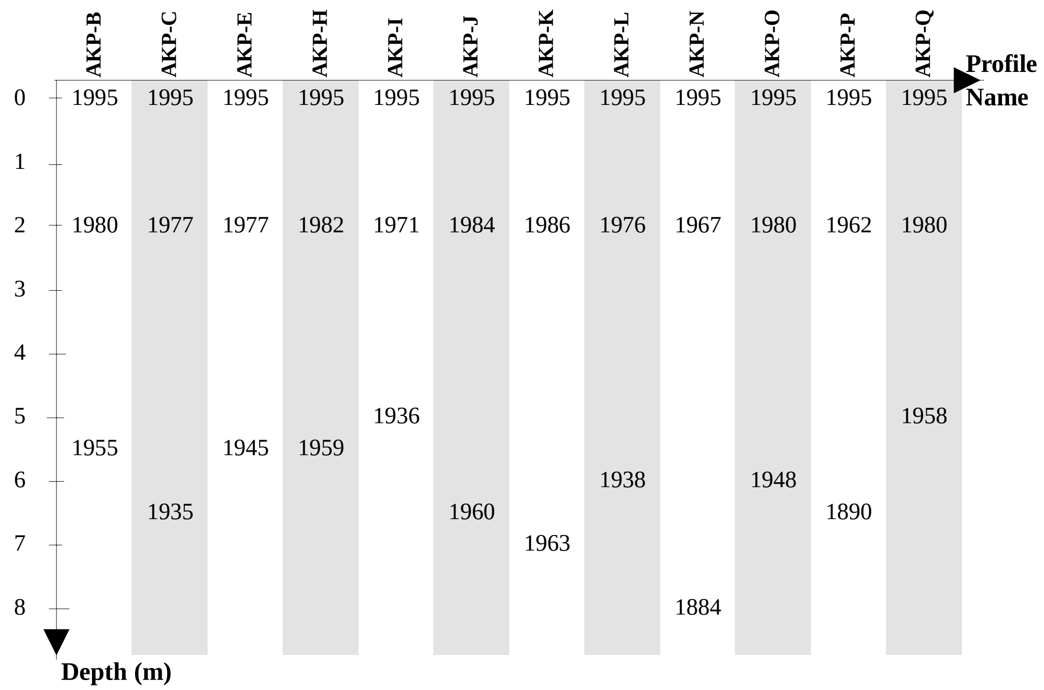


Fig. 6 Dates of recharge history recorded at Angunakolapellessa

(Note: The recharge history is available from 2 m depth downwards in each profile up to the date indicated at the bottom. e. g., for AKP-B the recharge history is available from 1955 to 1980).

From Fig. 6, it is seen that chloride fluxes are available for all the profiles from 1960 to 1967, except for profile P (where fluxes are available only before 1962) and K (where fluxes are available only after 1963). Therefore, it is possible to compare the estimates of recharge for the period 1960 - 1967 in all profiles except for profiles P and K.

Hence, considering only the depth in each profile represented by the period 1960 - 1967, the recharge rates were calculated from equation 1 for the location Angunakolapellessa and the results are shown in Table 4. (Rain and chloride concentration in rain were assumed as presently available values as no data is available for the said period. However, the error caused by this assumption is negligible as the exact values of these two parameters are not required for the comparison of recharge rates at the same location).

Table 4 No of years of recharge history recorded in each profile at location Angunakolapellessa

Sampling point	**5 year mean annual rain (mm/y)**	**Amount of rain infiltrating (mm/y)**	**Average chloride concentration of rain (mg/l)**	**Depth of 1967 flux[1] d1 (m)**	**Depth of 1960 flux[2] d2 (m)**	**Mean chloride concentration of soil between d1 and d2 (mg/l)**	**Estimate of recharge for mean chloride concentrations between d1 & d2 (mm/y)**
AKP-B	1091	709	4.4	3.83	4.79	390	8
AKP-C	1091	709	4.4	3.11	3.89	369	8
AKP-E	1091	709	4.4	3.06	3.82	308	10
AKP-H	1091	709	4.4	4.34	5.42	313	10
AKP-I	1091	709	4.4	2.32	2.89	326	10
AKP-J	1091	709	4.4	5.11	6.39	298	10
AKP-L	1091	709	4.4	2.98	3.73	263	12
AKP-N	1091	709	4.4	1.99	2.48	138	23
AKP-O	1091	709	4.4	3.63	4.54	322	10
AKP-Q	1091	709	4.4	3.71	4.64	562	6

[1] *Depth of soil water flux originated in 1967*
[2] *Depth of soil water flux originated in 1960*

The recharge estimates in the last column of Table 4 shows the estimates of recharge for different sampling points at Angunakolapellessa, considering only the period 1960 to 1967. The CV of these values is 0.42 which is similar to the CV value obtained by considering the full profile (0.40). A similar exercise was carried out for other locations as well and Table 5 gives the summary. For locations Buweliara, Kalpitiya and Maha Illuppallama, the recharge periods recorded in different profiles do not overlap and therefore it is not possible to compare the effect of using the same time periods in C_z in equation 1 on the spatial variability of recharge at a location. Even at the locations where this effect can be considered, not all the profiles can be used, for the same reason.

Table 5 Summary of Recharge estimates by chloride method at locations in Sri Lanka for specific time periods

Location	Period of recharge history considered	No of profiles considered	Minimum estimate of recharge (mm/y)	Maximum estimate of recharge (mm/y)	Mean estimate of recharge for the location (mm/y)	St Dev of recharge estimates at the location (mm/y)	CV	CV from Table 2
EMB	1987 - 1990	5	52	100	80	25	0.31	0.30
MID	1938 - 1964	6	7	20	14	4	0.33	0.64
AKP	1960 - 1967	10	6	23	11	5	0.43	0.40

From Table 5, it is evident that the spatial variability exists even after considering the same time period at each location. The last column of Table 5 shows the CV for each location considering the full depth of the profile augured (calculated earlier in Table 2) and the penultimate column shows the CV considering the same time period. Except for location Middeniya the CV's are similar and therefore it is very likely that the spatial variability is not because of considering different time periods in different profiles in the same location.

5 CONCLUSIONS

The following can be concluded from this study.

(i). Estimates of recharge when obtained by the unsaturated zone chloride profiling method (in the customary way) show spatial variability over small areas (1 ha) in the dry zone of Sri Lanka, as reported for various other places of the world.

(ii). This spatial variability appears to be true variability rather than an artefact of the chloride method used to estimate recharge, as the likely experimental error or uncertainties in the chloride method cannot explain the spatial variability.

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